

AUTOMATIC CONTROL ALGORITHM EFFECTS ON ENERGY PRODUCTION

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ABSTRACT

Algorithm control strategy for unattended wind turbine operation is a potentially important aspect of wind energy production that has thus far escaped treatment in the literature. Early experience in automatic operation of the Sandia 17-m VAWT has demonstrated the need for a systematic study of control algorithms. To this end, a computer model has been developed using actual wind time series and turbine performance data to simulate the power produced by the Sandia 17-m VAWT operating in automatic control. The model has been used to investigate the influence of starting algorithms on annual energy production. The results indicate that, depending on turbine and local wind characteristics, a bad choice of a control algorithm can significantly reduce overall energy production. The model can be used to select control algorithms and threshold parameters that maximize long-term energy production. An attempt has been made to generalize these results from local site and turbine characteristics to obtain general guidelines for control algorithm design.

INTRODUCTION

A computer model has been developed using real data to simulate power production of a vertical axis wind turbine (VAWT). The purpose of the model is twofold. First, to develop guidelines in control algorithm strategies. This basic step was initially undertaken with using data particular to the Sandia/DOE 17-m VAWT. These initial results are very interesting and have been useful in the automatic control program for the 17-m.

The second purpose of the model is to provide more general information on the energy available to a VAWT that is lost in the automatic control process. This information will, in turn, be used in the economic selection process of VAWTs for site specific cases.

The automatic control simulation model is discussed in section 1, the algorithms on the Sandia/DOE 17-m turbine are described in section 2, and the first step results are presented in section 3. In section 4, the specific first step results are generalized in an attempt to be applicable in a turbine selection process.

THE COMPUTER MODEL

The computer model was originally designed to simulate the 17-m VAWT in automatic control in Albuquerque, New Mexico, and as such was based on two sets of experimental data. The first data set is the electric power versus windspeed data collected using the method of bins (Ref. 1) for the 17-m operating at 50.6 rpm. A plot of the power curve used appears in Fig. 1.

The second set of data used is a collection of 890 hours of .5 Hz time series data of windspeed over 43 periods recor-

ded during weekends and nights of Summer-Fall 1979. The probability density function is plotted versus windspeed for the wind data in Fig. 2. The mean value of windspeed for the wind data is 11.1 mph which is above the actual Albuquerque mean annual windspeed.

The actual computer model is a Fortran program in which the electric power versus windspeed data are used to determine the power available at every point of wind data. If the turbine is stopped, the control algorithm will use this information to decide if the turbine should be started. If the turbine is running, the power is summed to determine the energy generated.

The overall energy output that is computed for a particular control algorithm depends on how long and when the turbine is running, as well as the number of starts. The number of starts is used by subtracting the energy consumed in all the starts from the calculated energy produced when the turbine is running. For the 17-m turbine, each start consumes approximately .6 kW-hr.

The output of the auto control simulator is given as an algorithm efficiency, and a number of starts occurring over the duration of the wind data. The notion of algorithm efficiency will be given a precise meaning following the preliminary notion of energy available to a wind turbine.

Energy Available. The energy available to a wind turbine is that amount of energy that would be produced by a turbine operating under an ideal algorithm. This quantity may be calculated from the electric power data directly by integrating the power produced over all times the power is positive, or by using the windspeed distribution function for positive powers.

Algorithm Efficiency. The algorithm efficiency is the percent the energy produced is of the energy available for a turbine operating under the algorithm control.

ALGORITHMS TESTED

Five different algorithms have been tested in parametric studies by the automatic control simulator. The first four algorithms have two parameters which are adjusted to find the optimum operating values. These two parameters are referred to frequently and will thus be formally defined.

Turn On/Off Threshold. The turn on/off threshold is the minimum value of average windspeed or average power that is required to start/stop the turbine by a decision loop of a control algorithm.

Test Window. The test window is the duration of the test period over which the average windspeed or power is calculated for comparison with the turn on threshold.

We may now name and describe the five algorithms tested as follows.

1) Discrete Windspeed Averages - At the end of each test window, the average windspeed over the test window is compared to the turn on threshold. If the test fails, a new average is begun and not tested again until the end of another test window. If the average windspeed is above the turn on threshold, the turbine is started. During turbine operation, the average windspeed is tested against the turn off threshold at the end of each test window for a stop decision.

2) Moving Windspeed Algorithm - After each point of windspeed data, a new average windspeed is calculated over the most recent test window. If the turbine is off, the average windspeed is tested against the turn on threshold to decide on a turbine start. If the turbine is on, the average is compared to the turn off threshold. After a start or stop, a 60 second blind period is introduced to simulate an actual start or stop.

3) Moving Power Algorithm - At each windspeed point, a value of power is read from the electric power versus windspeed data. From the power data, a running power average is calculated over the test window and compared to the turn on or on turn off threshold for a start or stop.

4) Discrete, Double Power Algorithm - At the end of each test length, two power averages are calculated. One for the average over the entire test window, and second, for the last one-tenth of the test window. Both averages must be greater than the threshold value for a start to occur. Stops are based on a test of the average power over the entire test window.

5) Canadian Coast Algorithm - Certain Canadian VAWT systems have utilized a semi-mechanical control system with an overrunning clutch on the high speed shaft to permit the rotor to coast when below synchronous speed. This system could conceivably reduce motoring losses in low wind conditions and simplifies the turn off condition which can be based on a simple rpm measurement.

From a cold stop, one of the first four algorithms is used to decide if a start should be initiated by a starting motor which takes the turbine to some fraction of the synchronous rpm. The turbine is then allowed to coast until either synchronous speed is reached, at which time the generator engages, or 5 minutes has elapsed and the turbine falls below a turn off threshold value of rpm. If synchronization is reached, when the torque at the high speed shaft becomes negative, the generator disengages and the coast cycle begins again. Whenever the rotor is coasting, the system generator is assumed to motor without shaft load at synchronous speed. Windage losses in the generator are accumulated during the coast period. The only parameter is the turn off threshold rpm.

RESULTS OF PARAMETRIC STUDIES

The results of the parametric computer runs for the five algorithms are plotted in Figs. 3 through 7. The maximum curves from each of the algorithms are plotted together in Fig. 8 to facilitate comparing the results. The following points are clear from the figures.

1) For each algorithm, a choice of the parameters can be made which will maximize the algorithm efficiency, and minimize the number of starts or coast time.

2) The algorithms may be ranked according to the maximum algorithm efficiency as follows:

- a) Canadian coast algorithm - 93.7%
- b) Moving power algorithm - 93.4%
- c) Discrete, double power algorithm - 92.8%
- d) Discrete windspeed algorithm - 92.3%
- e) Moving windspeed algorithm - 91.6%

3) A bad choice of parameters, particularly the test window, will greatly reduce the algorithm efficiency.

APPLICATIONS TO VAWT ECONOMICS

The algorithm control study of the previous sections is useful in maximizing energy production once a particular turbine and site have been selected. However, if a turbine is badly matched to a site, the maximum algorithm efficiency

may be as low as 72% as shown in an example below. It is clear then that control algorithm considerations will have an effect on the economics of wind energy production.

In order to utilize control algorithm properties in wind energy economics, it is necessary to determine if the maximum algorithm efficiency depends functionally upon a suitable composition of a local windspeed probability distribution function (PDF) with a turbine electric power curve (EPC). Since the windspeed PDF and the turbine EPC are both functions of windspeed, it is natural to construct the energy distribution function (EDF) from the two, which at any windspeed gives the fraction of the annual energy produced by the machine at that windspeed. The EDF is constructed as the normalized product of the PDF and the EPC. We will concentrate then on quantifying the dependence of the maximum algorithm efficiency upon the EDF.

The five types of algorithms discussed in section 2 were initially tested using the EPC from the Sandia/DOE 17-m VAWT. The EPC was determined experimentally by the method of bins, and the windspeed time series was recorded at the 17-m test site in Albuquerque, New Mexico. Clearly, a generally applicable relation between the maximum algorithm efficiency and the EDF cannot be found from the results of one specific set of turbine and windspeed time series data. Therefore, an expanded data base has been acquired including one additional set of windspeed time series data, and several other sets of turbine EPC's. The windspeed time series consists of a year of data recorded by the National Severe Storm Laboratory from the WKY tower in Oklahoma City, Oklahoma from October 1, 1976 to November 26, 1977. Most of the readings were taken at a sample rate of 0.1 Hertz. The data set includes windspeed, wind direction, temperature, and vertical velocity at 7 elevations, as well as pressure, wet bulb temperature, pyrometer, and rain gauge readings from selected elevations. The data were transcribed to 9 track magnetic tape and made available for dissemination by the National Center for Atmospheric Research. The windspeed data recorded at an elevation of 26 meters were used in the model since this elevation closest matches the equatorial elevation of VAWTs of interest. The PDF of the windspeed time series is closely approximated by the Rayleigh distribution with a mean windspeed of 10.4 mph (Fig. 9).

In addition to the Sandia/DOE 17-m EPC, two other types of EPC's have been used. The first type is generated by the computer code PAREP (Ref. 2) for a 17-m VAWT operating at 25, 30, 35, 40, and 45 rpm's. The second set of EPC's come from a one parameter family of piecewise linear curves defined by the function

$$P(V) = \begin{cases} -6kW & \text{for } 0 \leq V \leq V_0 - 2.2 \\ 2.7*(V - V_0) & \text{for } V_0 - 2.2 \leq V \leq 3*V_0 - 6.6 \\ 5.4*(V_0 - 18) & \text{for } 3*V_0 - 6.6 \leq V. \end{cases}$$

The parameter V_0 is the cut in windspeed, satisfying $P(V_0) = 0.0$. This family of EPC's was chosen to give a wide variation in turbine characteristics depending on only one parameter.

Automatic control simulator tests conducted subsequent to the introduction of the additional windspeed time series and turbine EPC's have been made using only the "moving power" algorithm since this algorithm so clearly outperformed the three other purely electronic control algorithms, and was nearly equal to the coast type algorithm.

The dependence of the maximum algorithm efficiency on the EDF may take any number of possible forms. After finding the maximum algorithm efficiencies for several cases by running many tests of the automatic control simulator corresponding to different data sets, plots were made of the maximum algorithm efficiency versus various properties of the EDF's. Two clear relationships emerged in the plots, either of which may be used to determine the approximate maximum algorithm efficiency corresponding to a given EDF. The first relationship is between the maximum algorithm efficiency and the slope of the EDF at the cut in windspeed, denoted E_0 . The plot of the maximum algorithm efficiency versus E_0 appears in Fig. 10. The second relationship is between the maximum algorithm efficiency and the ratio

$$R = \frac{V_m - V_0}{V_0}, \quad (1)$$

where V_m is the windspeed at the maximum EDF, and V_0 , as before, is the cut in windspeed. The plot of the maximum algorithm efficiency versus R appears in Fig. 11.

From Figs. 10 and 11 it is apparent that the maximum algorithm efficiency may be given as a function of either E_0 , the slope of the EDF at V_0 , or the ratio, R , defined in Eq. (1). This functional relation may be used in a VAWT economic selection process for a given site, or more basically, in determining if a VAWT is badly suited controlwise for a turbine site, as the Sandia 17-m turbine is for Oklahoma City with a maximum algorithm efficiency of 72%.

REFERENCES

1. Akins, R.: Performance Evaluation of Wind Energy Conversion Systems Using the Method of Bins - Current Status, SAND77-1375, March 1978.

2. Leonard, T.: A User's Manual for the Computer Code PAREP, SAND79-0431, April 1979.

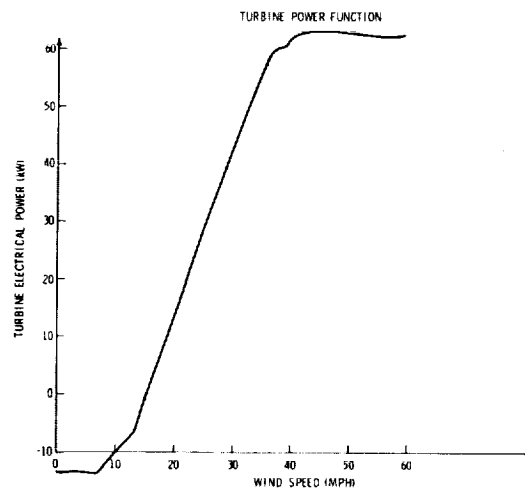


FIGURE 1

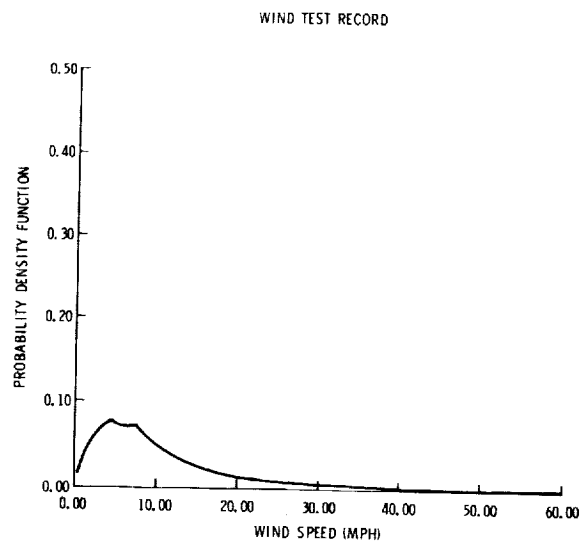


FIGURE 2

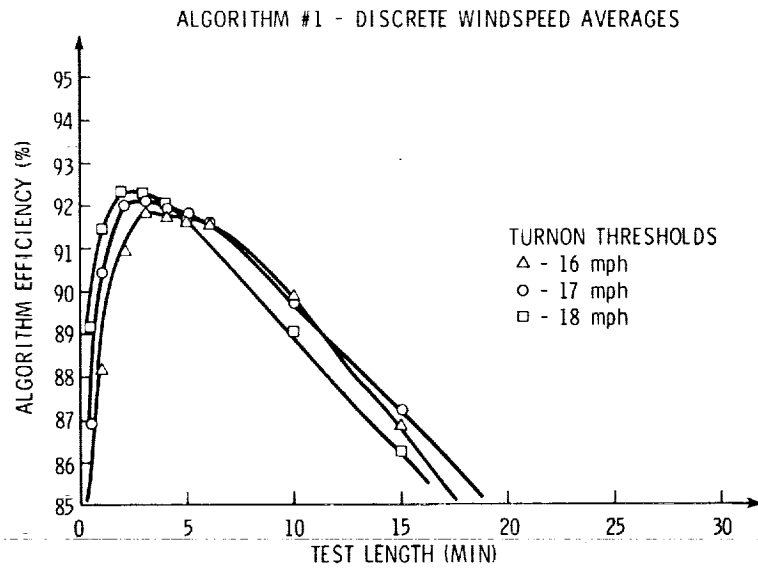


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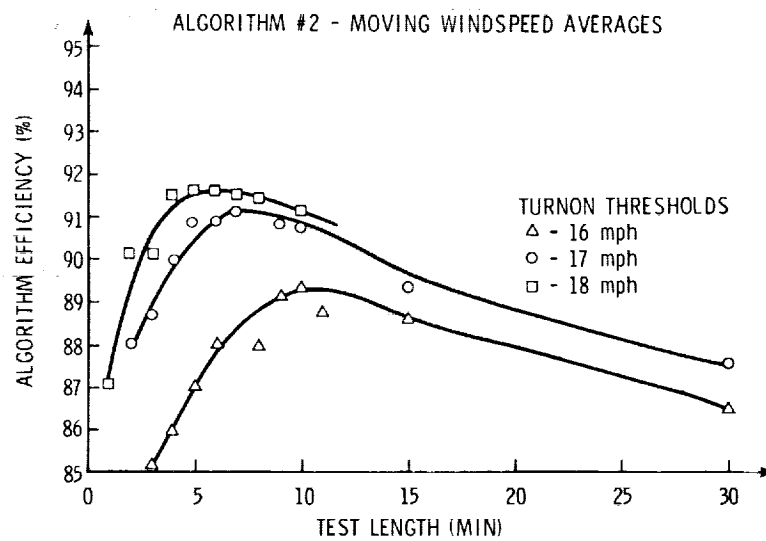


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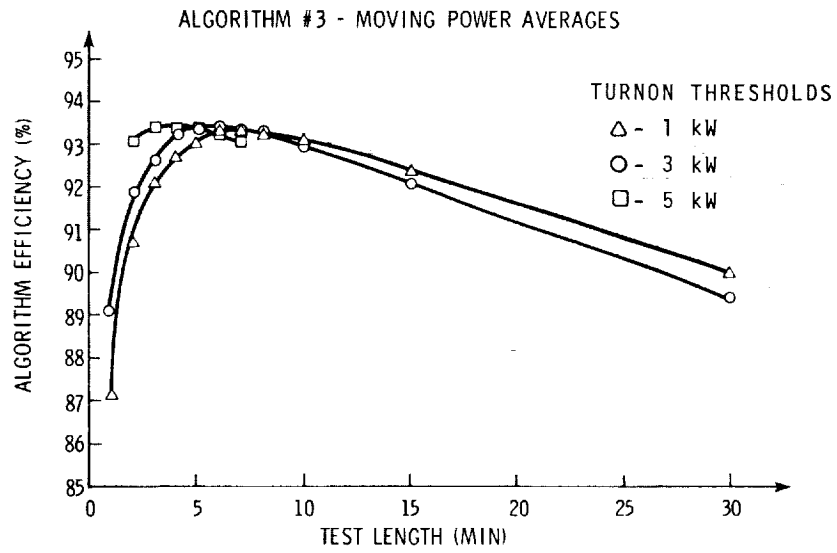


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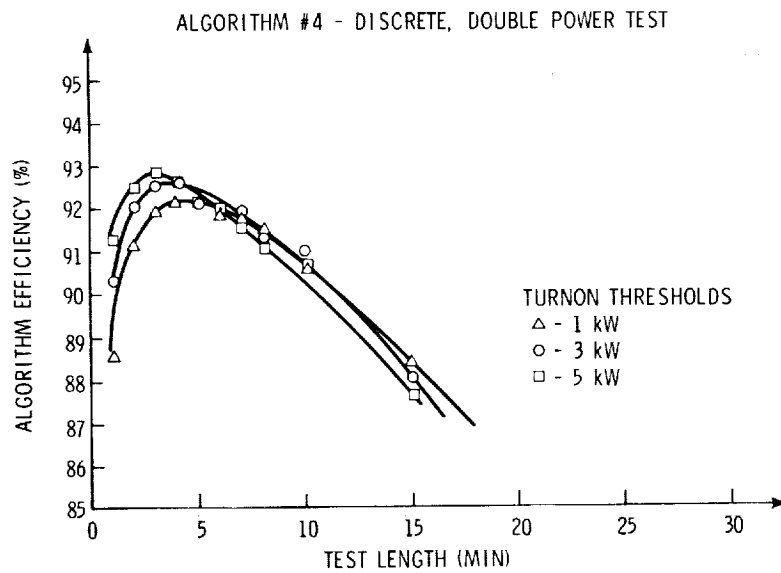


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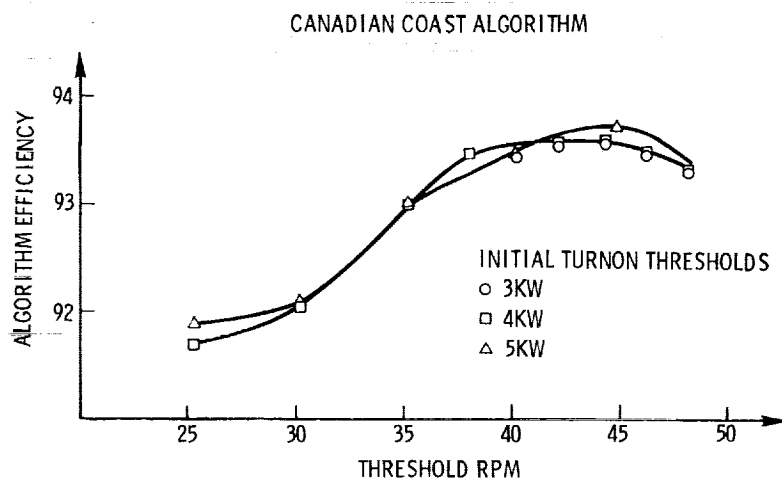


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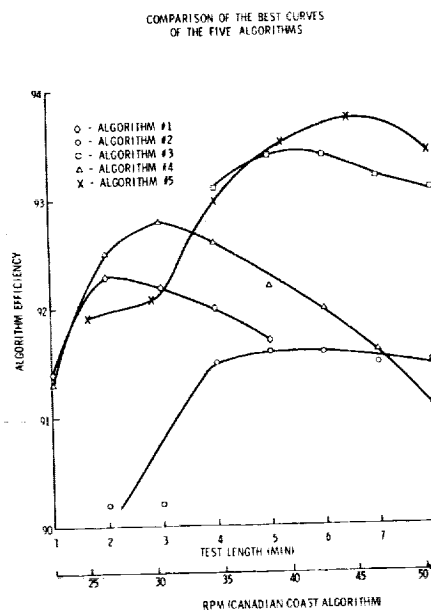


FIGURE 8

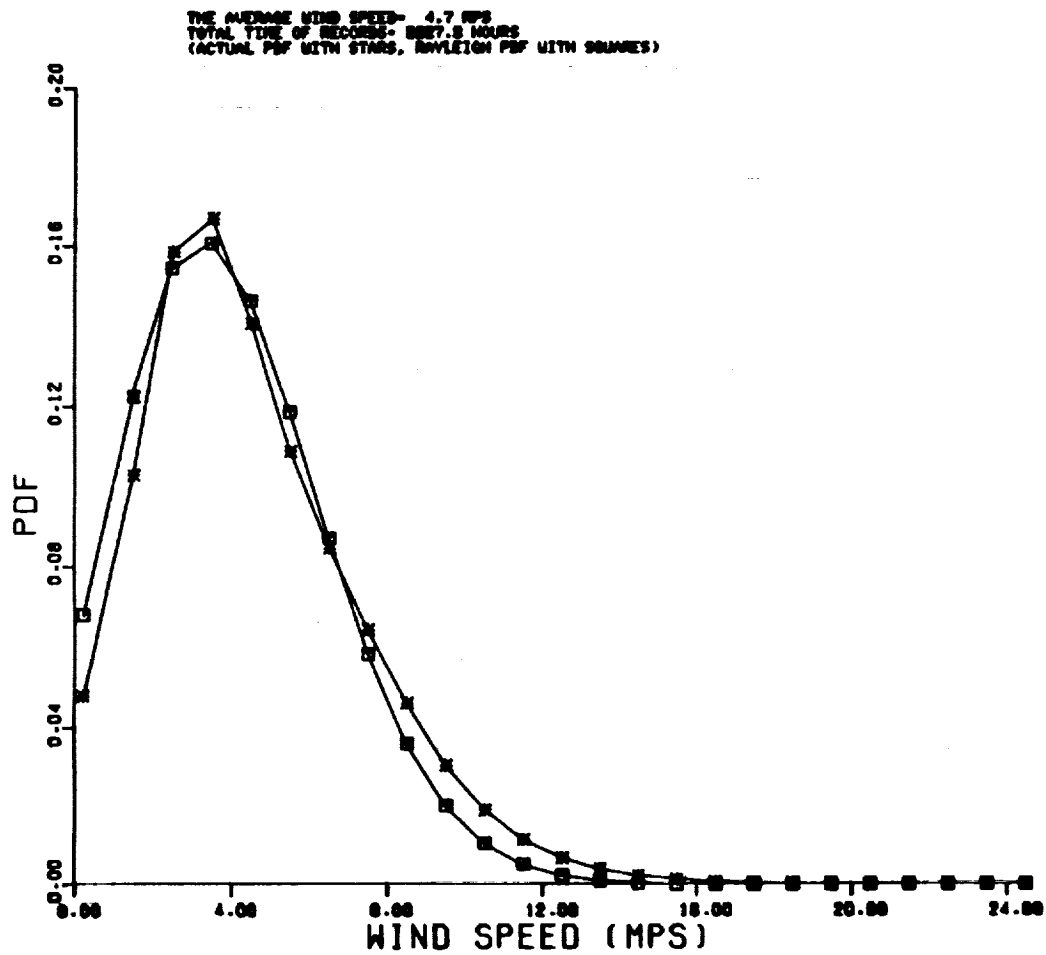


FIGURE 9 - Comparison of WKY Tower PDF with Rayleigh PDF

FIGURE 10

X Local Wind, 17-m
 * Local Wind, Piecewise Linear
 □ Local Wind, PAREP
 ○ Oklahoma Wind, Piecewise Linear
 ● Oklahoma Wind, Piecewise Linear
 △ Oklahoma Wind, Piecewise Linear

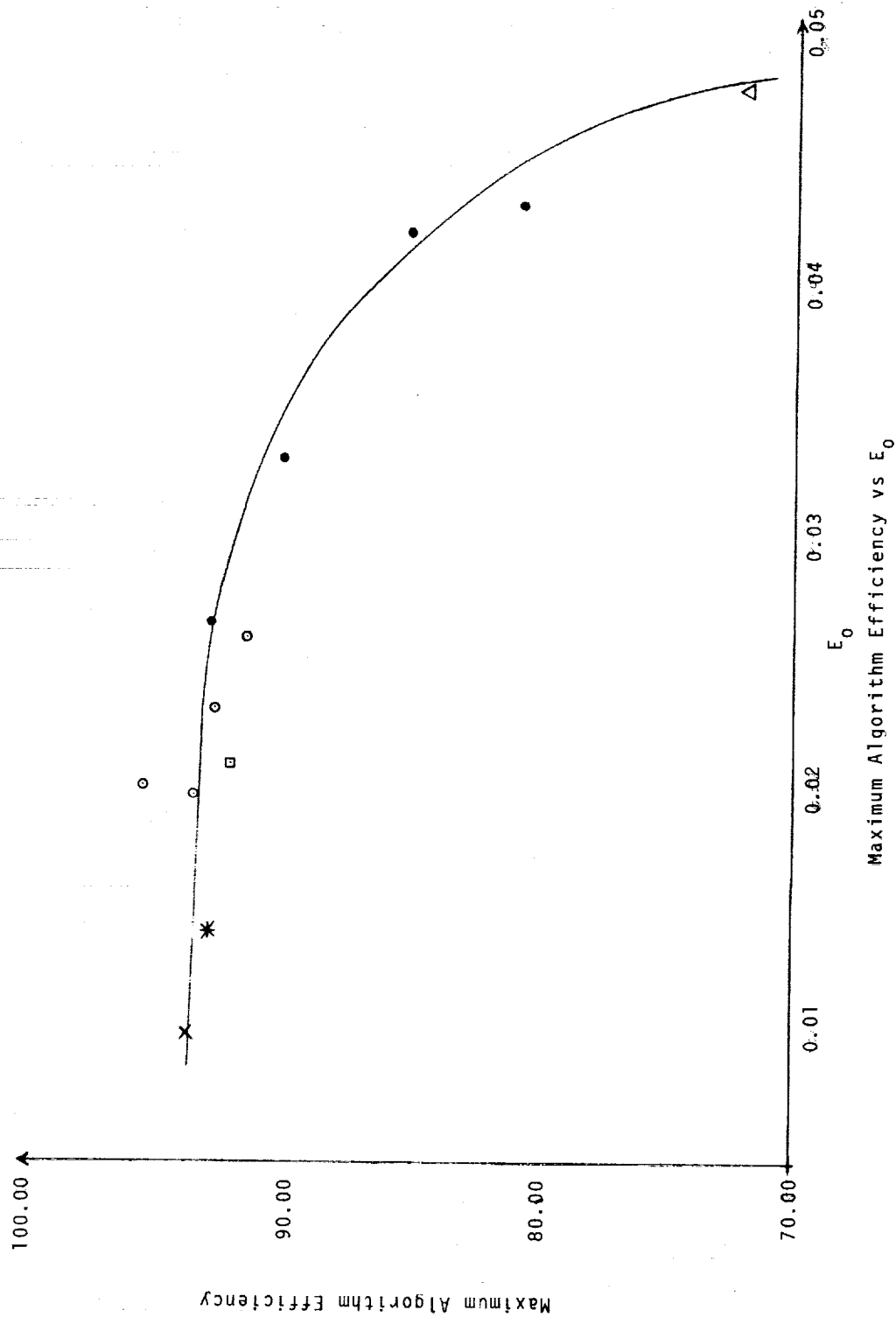


FIGURE 11

X Local Wind, 17-m * Local Wind, Piecewise Linear o Oklahoma Wind, PAREP
 □ Local Wind, PAREP ● Oklahoma Wind, 17-m • Oklahoma Wind, Piecewise Linear

